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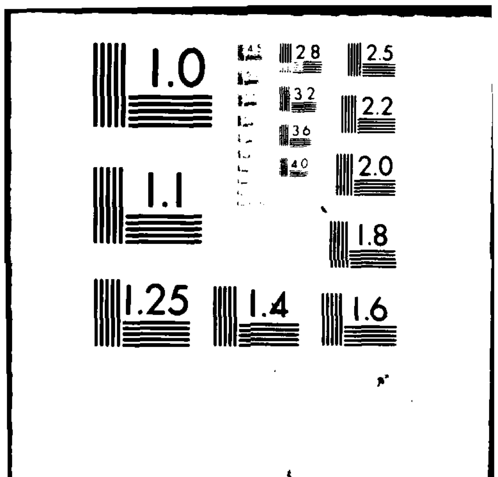

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# Some Observations on the Economics of "Overdesigning" Rubble-Mound Structures with Concrete Armor



by

J. Richard Weggel

COASTAL ENGINEERING TECHNICAL AID NO. 81-7

JUNE 1981



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A cost comparison is made between two designs for a revetment-breakwater using concrete armor units. Both designs used the same type of unit (dolosse); however, two different stability coefficients were used in the designs. The comparison shows that significant decreases in armor unit size may result in only insignificant cost savings and even cost increases for some conditions. This occurs because more smaller units are required to armor a given structure surface area, and any savings in material costs is offset by the increased cost of forming, stripping, and placing a greater number of smaller units.

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## PREFACE

This report compares cost figures for a dolosse revetment-breakwater using a higher stability coefficient ($K_D$) than that recommended in Chapter 7 of the Shore Protection Manual (SPM). A recalculation of the cost, based on the new $K_D$, provided some interesting observations on the consequences of "overdesigning" a dolos-armored structure. The work was carried out under the coastal structures research and development program of the Coastal Engineering Research Center (CERC).

The report was prepared by Dr. J. Richard Weggel, Chief, Evaluation Branch, under the general supervision of N. Parker, Chief, Engineering Development Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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## FIGURES

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

| Multiply | by | To obtain |
|---|---|---|
| inches | 25.4 | millimeters |
| | 2.54 | centimeters |
| square inches | 6.452 | square centimeters |
| cubic inches | 16.39 | cubic centimeters |
| feet | 30.48 | centimeters |
| | 0.3048 | meters |
| square feet | 0.0929 | square meters |
| cubic feet | 0.0283 | cubic meters |
| yards | 0.9144 | meters |
| square yards | 0.836 | square meters |
| cubic yards | 0.7646 | cubic meters |
| miles | 1.6093 | kilometers |
| square miles | 259.0 | hectares |
| knots | 1.852 | kilometers per hour |
| acres | 0.4047 | hectares |
| foot-pounds | 1.3558 | newton meters |
| millibars | $1.0197 \times 10^{-3}$ | kilograms per square centimeter |
| ounces | 28.35 | grams |
| pounds | 453.6 | grams |
| | 0.4536 | kilograms |
| ton, long | 1.0160 | metric tons |
| ton, short | 0.9072 | metric tons |
| degrees (angle) | 0.01745 | radians |
| Fahrenheit degrees | 5/9 | Celsius degrees or Kelvins[1] |

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: C = (5/9) (F -32).

To obtain Kelvin (K) readings, use formula: K = (5/9) (F -32) + 273.15.

# SOME OBSERVATIONS ON THE ECONOMICS OF "OVERDESIGNING" RUBBLE-MOUND STRUCTURES WITH CONCRETE ARMOR

*by*
*J. Richard Weggel*

## I. INTRODUCTION

Development of the design problem presented in Chapter 8 of the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977)[1] provided an opportunity to calculate the relative cost of a revetment-breakwater on the seaward side of a hypothetical manmade island armored with concrete armor units built at various slopes with various concrete unit weights. One type of armor unit evaluated was the dolos. The recommended stability coefficient $(K_D)$ for dolosse was 13.6 when the initial calculations were made. The stability coefficient was subsequently raised to 25.0 based on the results of hydraulic model tests. This change led to a comparison of cost figures for the dolosse revetment-breakwater designed using $K_D = 25.0$ with one designed using $K_D = 13.6$. A recalculation of the cost of the dolos-armored structure using the new, nearly doubled, stability coefficient, gave some interesting observations regarding the consequences of overdesigning, and are presented in this report.

This report deals primarily with the first cost of a structure, not its average annual cost which is the sum of its first cost amortized over the structure's economic life and the average annual cost of repairing the structure following events that exceed design conditions; however, the results of the first-cost analysis have interesting implications regarding minimization of the risk of damage to the structure resulting from waves greater than the design wave.

The cost figures used in this analysis were based roughly on 1972 costs and, because of the academic, illustrative nature of the original problem, were only approximately based on real costs associated with the rehabilitation of the Humbolt jetties at Eureka, California, in 1970-72. Consequently, the cost figures should not be assumed valid today or even to have been valid in the 1970-72 time frame. What is important to the conclusions presented is the relative change in cost arising from a substantive change in stability coefficient. Other important economic and physical design factors, some of which may be peculiar to dolosse and others generally applicable, are not considered here. For example, structures requiring larger dolosse may need to be designed using lower stability coefficients in order to preclude motion that could break the units; i.e., there may be a scale effect. This factor might be perculiar to dolosse because of their fragility compared to other, stouter units. Another factor not considered is the influence of increasing the armor unit size on construction equipment requirements. Increasing armor unit size beyond a certain point will require increasing the capacity of handling and transporting equipment such as cranes, trucks, barges, etc. Consequently, the cost of casting, stripping, handling, and placing individual concrete armor units is not independent of armor unit size but increases with size even after material cost

[1]U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 3d ed., Vols. I, II, and III, Stock No. 008-022-00113-1, U.S. Government Printing Office, Washington, D.C., 1977, 1,262 pp.

increases are deducted. In fact, the relationship must increase in a discontinuous way. Small to moderate increases in armor unit weight should have little or no effect on cost since the same equipment can be used to handle slightly larger units. However, when armor unit weight exceeds some limit, larger construction equipment is required and the cost jumps up. For the example in this report, the cost of casting, stripping, handling, and placing individual units (exclusive or material costs) was assumed constant. The relative cost of core material, underlayer stone, and armor are also important. A most important factor affecting the result is the proportioning of total armor layer cost between the relative costs of labor and materials.

Another factor related to armor unit size must be kept in mind when large concrete armor units (740 tons) are being considered. As concrete units increase in size their *relative* strength decreases and the possibility of breakage increases. The weight of an armor unit increases with its volume or with the cube of its length dimension. Its strength, if unreinforced, increases only with the square of its length dimension; hence, in the extreme, an armor unit could break under its own weight. This factor must be taken into account when an increase in armor unit weight is being considered. Conceivably, the no-damage stability coefficient for large armor units could be a function of their weight.

Additionally, the results obtained in the analysis may not be uniformly valid to all rubble-mound design problems. Economic analyses are highly site-specific and thus no general analysis is ever totally valid for any real project. The analysis presented should, however, illustrate a need to investigate several rubble-mound alternative structures for various levels of design.

## II. ANALYSIS

A typical cross section for the armored side of a hypothetical island in the mouth of Delaware Bay is shown in Figure 1. Basically, it represents a typical rubble-mound structure cross section with armor on only one side. The leeward side is the interior of the island. The crest elevation was established to preclude overtopping by a wave 18 feet (5.5 meters) high with the wave period selected to result in maximum runup. (Details of the design problem are given in Ch. 8 of the SPM.) The design significant wave height used in Hudson's (1958, 1959)[2,3] equation for armor unit weight was 18 feet.

[2]HUDSON, R.Y., "Protective Cover Layers for Rubble-Mound Breakwaters, Studies Completed Through March 1957," Miscellaneous Paper 2-276, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., July 1958.

[3]HUDSON, R.Y., "Laboratory Investigations of Rubble-Mound Breakwaters," *Proceedings of the American Society of Civil Engineers*, Vol. 85, No. WW3, 1959.

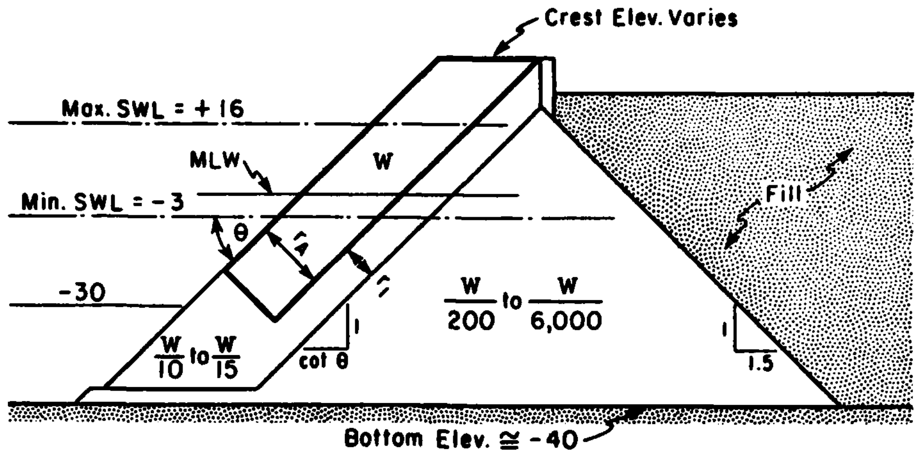


Figure 1. Preliminary rubble-mound cross section, hypothetical island (modified from Fig. 7-99 in the SPM).

The dolosse armor unit weights required were computed for structure slopes of 1 on 1.5, 1 on 2, 1 on 2.5, and 1 on 3, ($\cot\theta$ = 1.5, 2.0, 2.5, and 3.0, respectively) and for concrete densities of 150, 160, and 170 pounds per cubic foot (24.3, 25.9, and 27.5 kilonewtons per cubic meter). Hudson's equation is given by

$$W = \frac{w_s H^3}{K_D (S_r - 1)^3 \cot\theta}$$

where

- $W$ = weight of armor unit required for stability
- $w_s$ = unit weight of material of which armor unit is constructed
- $H$ = design significant wave height
- $S_r$ = ratio of unit weight of armor unit material to unit weight of water
- $\theta$ = angle structure face makes with a horizontal
- $K_D$ = a stability coefficient.

Hudson's equation was assumed to describe the relationship between required armor unit weight, design wave height, structure slope, and armor material unit weight. A zero-damage criterion was used. Some investigators (e.g., Bruun and Johannesson, 1974)[4] have suggested that Hudson's equation may not be valid for

[4] BRUUN, P., and JOHANNESSON, P., "A Critical Review of the Hydraulics of Rubble-Mound Structures," Report R3-1974, University of Trondheim, Division of Port and Ocean Engineering, The Norwegian Institute of Technology, Trondheim, Norway, 1974.

armor units such as dolosse or that other variables not considered by the equation are important; e.g., wave period is thought to be a factor but is not considered in Hudson's equation. While this may or may not be correct, any other armor stability equation could have been used in the analysis without significantly changing the conclusions presented in this report. Other stability equations might change the details of the results but would not change the following observations regarding relative economics of "overdesigning" armor layers.

Figure 2 presents the end result of the economic analysis for two sets of calculations for dolosse armor ($K_D$ = 13.6 and $K_D$ = 25.0). The set of intersecting curves to the right in the figure is for calculations with $K_D$ = 13.6; the curves to the left are for $K_D$ = 25.0. The figure presents the total first

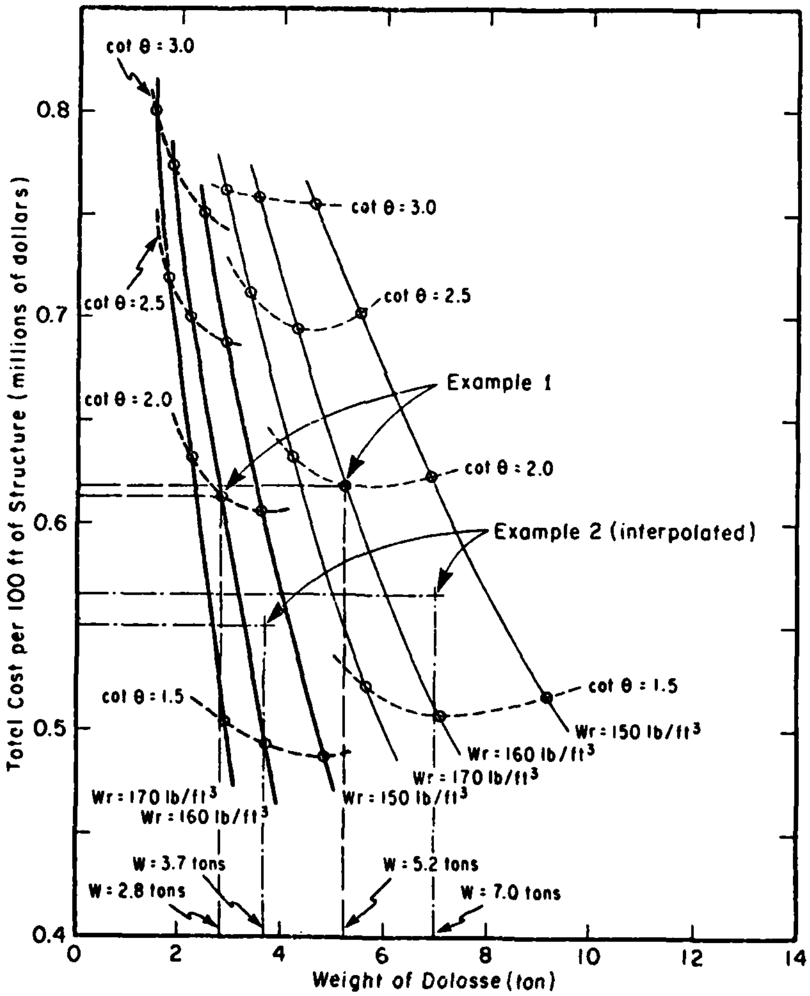


Figure 2. Total cost of 100 feet of structure as a function of structure slope, concrete unit weight, and dolosse weight for $K_D$ = 13.6 and $K_D$ = 25.0.

cost for 100 feet (30.5 meters) of structure as a function of dolosse weight, structure slope, and concrete unit weight. Each point in the figure represents a solution to the design problem. One solution (example 1 in Fig. 2), using the curves for $K_D = 13.6$, is that a structure with a 1 on 2 slope having a concrete unit weight of 160 pounds per cubic foot requires a 5.2-ton (4.77 kilonewtons) dolosse for armor against the 18-foot design wave. The cost for 100 feet of structure armored with a 5.2-ton dolosse is about $618,000. Another solution to the design problem (example 2 in Fig. 2) would be to use a 7-ton (6.42 kilonewtons) dolosse having a unit weight of 155 pounds per cubic foot (25.1 kilonewtons per cubic meter) placed on a 1 on 1.75 slope. The cost of this solution per 100 feet of structure is $565,000.

When the stability coefficient is increased to $K_D = 25.0$, the family of curves to the left in Figure 2 represents solutions to the design problem. The required dolosse weight has been nearly halved for equivalent conditions of structure slope and concrete unit weight. The cost per 100 feet of structure, however, has not changed appreciably; e.g., using $K_D = 25.0$ for conditions cited in example 1 above with a structure slope of 1 on 2 and a concrete unit weight of 160 pounds per cubic foot, the required dolosse weight has been reduced from 5.2 to 2.8 tons (4.77 to 2.51 kilonewtons) but the cost only decreased from $618,000 to $612,000 per 100 feet of structure. In example 2, the required dolosse weight is now only 3.7 tons (3.39 kilonewtons) rather than 7 tons but the cost has only decreased from $565,000 to $550,000 (2.7 percent) per 100 feet. In fact, for some conditions of structure slope and concrete unit weight the cost actually increases for the larger stability coefficient and smaller armor units. This generally occurs for flatter slopes and higher values of concrete unit weight.

The explanations for the relatively small change in cost with smaller armor units are that (a) the cost of the armor layer may represent a relatively small percentage of the total cost of the structure, especially for flat-sloped structures that have large quantities of core material, and (b) the relative cost of labor compared with the cost of materials used to construct armor units is high and results in an increase in the cost of armor. Labor costs in casting concrete armor units are sensitive to the *number of units* that need to be formed, stripped from forms, reinforced (if necessary), transported, and placed on the structure. The cost of materials on the other hand is simply proportional to the amount of materials needed. As the size of armor units decreases, the number of units required to cover a given structure surface area increases and, along with it, the cost of labor to form, strip, reinforce, transport, and place the units. The amount of concrete, reinforcing, etc., required to cover a given area in armor will decrease with decreasing armor unit size. Whether or not a cost saving is realized by decreasing armor unit size depends on whether the savings achieved by using less materials exceed any increase in labor costs resulting from using more armor units. The relative cost of labor versus materials is thus an important factor in establishing the optimum size armor unit. As the relative cost of labor increases, it becomes more economical to design using fewer, larger units, i.e., overdesigning the armor.

The way in which the foregoing factors influence a design is through selection of a design level, i.e., by selecting a design wave height which will result in the most economical structure by balancing the structure's first cost against annual maintenance costs, repair costs, and benefits foregone to achieve an overall least-cost design. Obviously, for a given armor unit shape, its

stability characteristics and thus its stability coefficient will not change (disregarding any changes brought about by additional testing). The designer is therefore dealing with a relatively constant characteristic of the armor unit. Figure 3 demonstrates how the preceding armor unit costs factors influence selection of a design level. The figure shows how the total average annual cost of a rubble structure varies with design wave height. If a large design wave height is selected, a more massive structure design results with a corresponding high first cost. The probability of the large design wave being exceeded in any given time period is relatively small and, therefore, the need to repair damage caused by waves larger than the design wave will be relatively small; consequently, the annual cost for maintenance and repair will be low. Also, since a large structure will be designed, the amount of protection afforded the area in its lee will be high, thereby providing greater economic benefits. In contrast, if a low design wave height is selected, a relatively cheaper, smaller structure will result from the design. This structure will have a lower first cost, but the probability of the low design wave being exceeded in a given time period will be relatively high. The average annual cost of maintaining and repairing the structure will also be high since the design wave height may be exceeded frequently. In addition, the smaller sized structure may not offer much protection to the area behind it because of the frequent damage. Benefits realized by the project may therefore be lower, or equivalently as shown in Figure 3, the

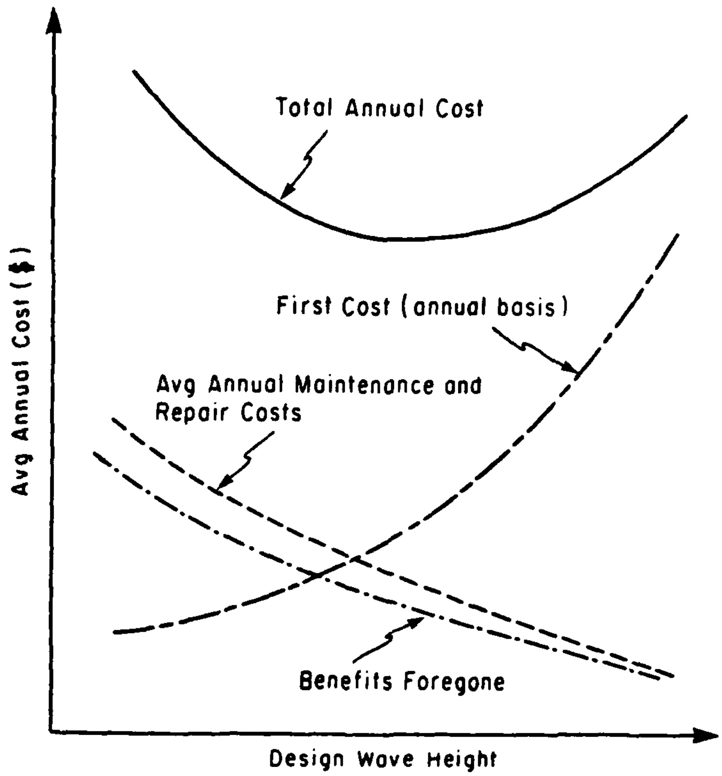


Figure 3. Relationship between first costs, maintenance and repair costs, benefits foregone, and design wave height.

benefits foregone will be higher. Even though structure first costs are low, the total average annual project cost may still be relatively high since annual costs for repair and maintenance will be high. An optimum design wave height between the preceding extremes will result in a structure that minimizes average annual project costs. This design level can only be found by investigating a range of design wave heights and assessing the costs and benefits associated with each.

The effect of the preceding observations on concrete armor unit costs of optimizing the design level is to give projects designed for larger waves an economic advantage. Designs for larger waves will have fewer armor units with only relatively small additional costs incurred for designing a larger structure, i.e., the curve labeled "First Cost" in Figure 3 will be relatively flat. If the added costs are sufficiently small, they will be more than offset by decreased maintenance and repair costs and increased project benefits. The effect, therefore, is to shift the minimum of the total cost curve in Figure 3 to the right toward higher design wave heights.

## III. SUMMARY AND CONCLUSIONS

The design of rubble-mound structures with concrete armor units should consider optimizing the design by investigating a range of possible design wave heights and the costs associated with each. This will result in a design which balances first costs against average annual maintenance and repair costs to obtain a least-cost structure. The relatively small change in overall structure first cost associated with a significant change in the recommended stability coefficient for dolosse armor suggest that it may be more economical to design using fewer larger armor units since a part of the cost of concrete armor is proportional to the number of units required. As the stability coefficient for an armor unit is increased, the amount of concrete and other materials required to armor a given area of the structure decreases; however, the number of units needed to cover the given area increases. Any savings in construction materials accrued by using smaller armor units are thus offset by increased labor costs needed to form, reinforce, strip, and place a greater number of units. This observation suggests that the minimum point on the total annual costs curve will be shifted toward the right to favor higher optimum design wave heights.

The effects of increasing armor unit size on their relative strength must be considered, particularly if large units are being considered.

It is recommended that designers of rubble-mound structures work closely with cost estimators to ensure that an optimum level of design is achieved. This can only be obtained if a range of design wave heights and corresponding structure designs is evaluated.

Weggel, J. Richard (John Richard)
Some observations on the economics of "overdesigning" rubble-mound structures with concrete armor / by J. Richard Weggel.--Fort Belvoir, Va., : U.S. Army Coastal Engineering Research Center : Springfield, Va. : available from NTIS, 1981.
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